Description of
bubble formation during freezing of water
in a cylindrical container

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Introduction

The neutrino telescope AMANDA, which is under construction at the south pole, uses a volume of the Antarctic glacier as a target for cosmic neutrinos. Vertical holes, 2 km long, are drilled using hot water. In each hole a string of light sensitive detectors are deployed. During the re-freezing of a hole, bubbles are formed in the ice creating a ”misty” core along the axis. Since the performance of the telescope depends strongly on the optical properties of the ice, it is important to try to reduce the amount of bubbles.

In the present work some features of bubble formation in ice are presented. A few illustrative experiments have been performed. These experiments are described, and their implications for AMANDA are discussed.

Bubble formation in ice [1]

Since the solubility for air in *solid ice* is poor compared with *liquid water*, any gas solved in the liquid will be forced out of the substance as it freezes. When ice is growing in water there will be a zone between the two phases of aggregation where the concentration of air is increasing. When the water becomes saturated bubbles form, and may attach to the ice surface. What happens then depends on the freezing rate:

- If the ice does not grow to fast, the bubbles will be pushed forward in front of the ice surface. The ice will be clear, without bubbles.

- With a higher freezing rate small bubbles may be captured between ice crystals. This influences the local geometry in a way that supports the probability of more bubbles being captured close to the previous ones. The process is repeated, resulting in thin tubes of air, parallel with the direction of ice growth.

- For still higher freezing rates bubbles will be captured more easily. Ice will simply freeze around them. With increasing freezing rates the *size* of captured bubbles will decrease while the *number* of bubbles will increase. The ice will become (more or less) non-transparent.

Freezing of ice cylinders

In a glacier hole the water freezes radially from the walls towards the axis. As the volume of liquid water decreases, the concentration of air raises. As the freezing proceeds the process of bubble formation accelerates. Even if the freezing rate initially is slow enough to produce clear ice, bubbles will be more abundant later on – closer to the axis. In the general case, a central core of non-transparent ice would be surrounded by a layer of ice with radial air tubes, and only the outermost region would be of the clear-ice type. In reality, the thickness of each layer will be determined by details like the freezing rate, the initial amount of solved air in the water and the value for the concentration of air which defines saturation...

The experiment

As a model for the re-freezing of glacier holes, an experiment was performed using a cylindrical metal container which was insulated in both ends, filled with tap water and put in a freezer. A small hole in the upper insulator allowed water to leak out as the pressure rose due to the expansion caused by the freezing. The dimensions of the container are presented in figure 1.

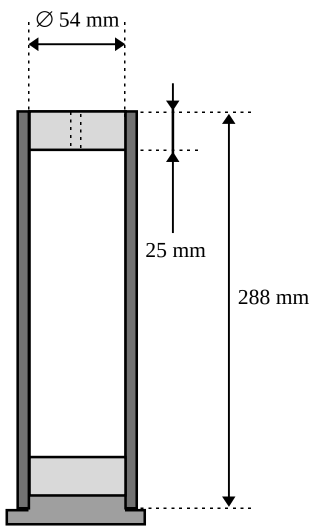

Figure 1. A cylindrical metal container was used for the freezing experiments. Both ends are insulated. The bottom of the container is sealed with a plastic lid.

The experiment was repeated a number of times, with small variations. However in all cases the same freezer was used. The freezing temperature (reached after a couple of hours) was -25°C. Over the vertical distance occupied by the container, the temperature in air was measured to be constant within 1°C. Below follows short summaries of the different experiments:

1) *Simple freezing of an ice cylinder*
The bubbly core was shaped like a cone with the base at the bottom. The core was surrounded by one layer containing air tubes and one layer of clear ice. Except for the conic shape this verifies the expected behaviour.

2) *Freezing with a hard rubber ball placed on the cylinder axis*
The detectors deployed at the south pole are spherical in shape. To investigate how the presence of these spheres affect bubble formation, an experiment was performed where a spherical rubber ball was placed at the cylinder axis. The bubbly cone looked the same as before except for the interruption of the rubber ball. Just below the ball larger bubbles had assembled. These probably formed after the ice walls reached the ball. Then the lower part of the container was cut off from the part above the ball. Bubbles being released, and rising from the ice surface in the lower part of the container could no longer escape, but was captured below the ball and thus forming the observed large bubbles.

3) *Registration of the water/ice temperature along the axis during the freezing process*
A thin wooden stick was placed along the cylinder axis to support three thermal sensors placed at different depths, one in the middle of the container, and the other two at one quarter of the container length from each end. The sensors were connected to a logging device, and the temperature was recorded for the three sensors every five minutes. The registration continued for ten hours, starting immediately after putting the container in the freezer. The temperature curves are presented in figure 2.

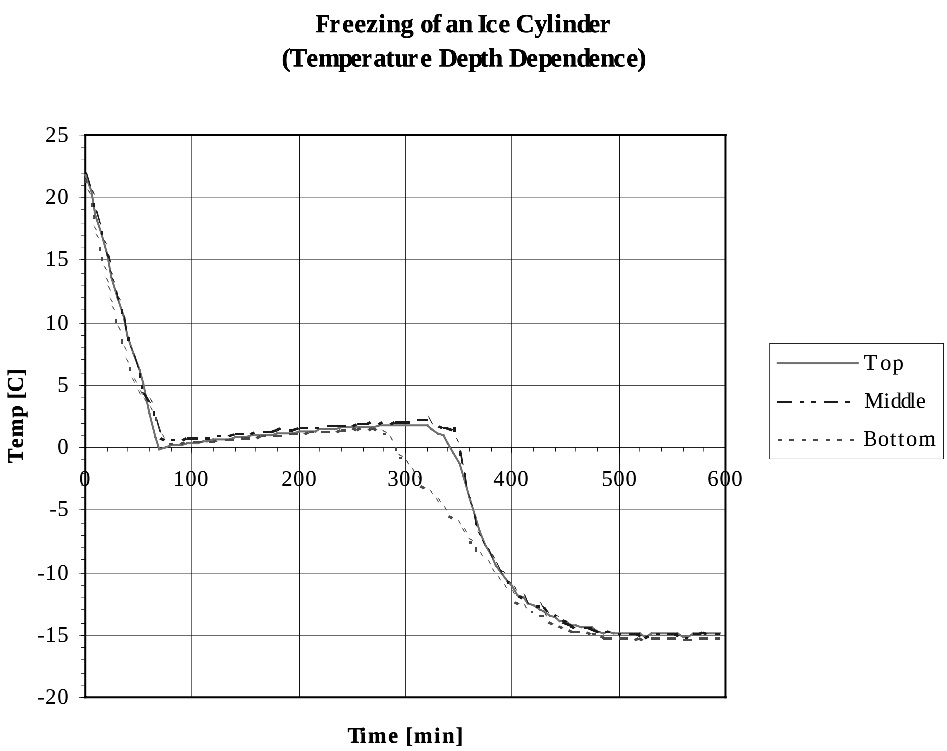

Figure 2. The temperature was measured at three different depths in the cylindrical container. After cooling to 0°C ice starts to build at the walls. Heat is released due to the phase transition. Temperature drops as the ice reaches the axis.

The first hour was spent cooling the water from room temperature to 0°C. Note, that at higher temperatures the water closer to the bottom of the container is colder than the water above. Since water of 4°C have the highest density, the curves cross at this temperature, leaving the lower regions of the container at higher temperatures than above.

When the temperature reaches 0°C ice starts to form on the walls. As a result of the phase transition from liquid to solid state, heat is released. Since the ice on the walls act as an insulator against the surroundings, some of this heat is transferred to the liquid resulting in a slow rise in temperature. All three sensors now measure the same temperature.

After some time the ice reaches the axis. This may be seen in the curves as a distinct drop in temperature. Note, that the freezing does not occur simultaneously along the axis. The drop occurs almost an hour earlier for the bottom sensor compared with the other two.

4) *Freezing of a cylindrical ice tube*

To verify that the freezing rate really is higher at the bottom, a new experiment was performed; but this time the freezing was disrupted after approximately three hours. The result was a cylindrical ice tube. The inner diameter of this tube was found to be smaller at the bottom than at the top, as expected. Also, it was noted that the ice at the bottom already had started forming the bubbly core, while the ice at the top was all transparent.

5) *Freezing with the container partially insulated*

An attempt was made to achieve a local reduction of the bubbly-core diameter. Around a segment of the metal container an insulating "collar" was attached. The purpose was to slow down the freezing rate in this region. As long as a larger volume of *liquid* water remains, the air concentration will not increase as fast as it normally would. With a normal freezing rate directly above and below this volume, the higher rate of bubble formation typical for bubbly-core ice, would be delayed. Thus, the core diameter would be reduced as intended. Note, that in the insulated section the effect is the opposite. After freezing is completed below and above this section a cavity with high air concentration will remain.

The observed result seems to agree with the described behaviour. The collar was placed around the upper half of the container, and along this section there was an increased core diameter compared with previous experiments. Above the insulated section the core diameter was small before, preventing any significant reduction from being determined. Any increase in core diameter *would* have been detected, but no such increase was observed. Below the insulated segment there was a significant reduction in the bubbly-core diameter, as expected!

Discussion

The purpose of the present work have been to gain information about the freezing process, and to make preliminary suggestions on how to reduce the amount of bubbles in the ice.

Observations are consistent with descriptions found in the literature, maybe with the exception of the *conic shape* of the bubbly-ice core. One possible explanation is that the conic shape is a result of heat transfer through the bottom of the container. An observation that supports this is the fact that the ice is growing faster at the lower end.

It has been shown that it may be possible to reduce the amount of bubbles locally. The method used in this experiment was to insulate a segment of the container. At the south pole other solutions would probably be more appropriate. It would for example be possible to let a segment of the hole, above the intended position of a detector, to have a larger diameter. Since it would take longer time for this wider segment to freeze, it would give a similar result as in the experiment. Another possibility to slow down the freezing rate would be to heat the water during the re-freezing period.

Future investigations should try to increase the resemblance with the situation at the south pole. There are many factors to consider. Here are a few examples:

- hole dimensions
- details in heat transfer to the surrounding ice
- water pressure
- air concentration in the water

Also, the model behaviour should be compared with measurements made at the south pole. Only then will it be possible to make credible and detailed predictions regarding the bubble formation during re-freezing.

Reference

[1] Gjutning av isbanor för biltestning
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http://www.luth.se/depts/lib/coldtech/ct92-4.html